Measurement of the inclusive jet and dijet cross sections using 2010 data from the ATLAS detector and calibration studies and simulation of the ATLAS forward calorimeter

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April 12, 2013

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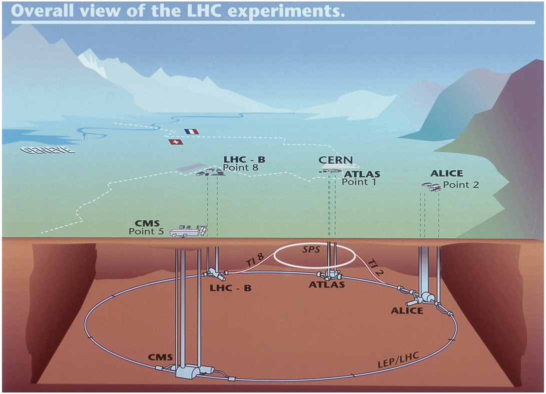
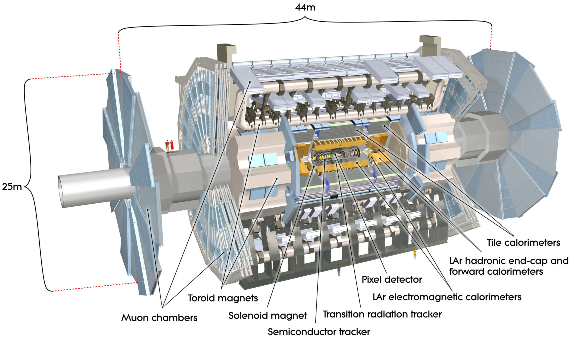
The Large Hadron Collider (LHC)



- 27 km circumference, 45-170 m underground
- Design luminosity of $10^{34}\mathrm{cm}^2\mathrm{s}^{-1}$, COM energy 14 TeV
- Achieved $2 \times 10^{31}\mathrm{cm}^2\mathrm{s}^{-1}$, 7 TeV COM during 2010.
- ATLAS, CMS multipurpose experiments

The Atlas Detector



$$\eta = -\log \tan\left(\frac{\theta}{2}\right)$$

- General purpose detector at the LHC
- Inner Detector: charged particle tracking for $|\eta| < 2.5$
- Calorimetry: energy measurement for $|\eta| < 4.9$
- Muon Spectrometry: $|\eta| < 2.7$

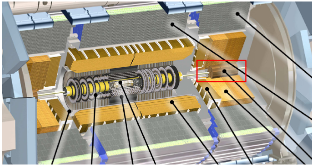
Trigger

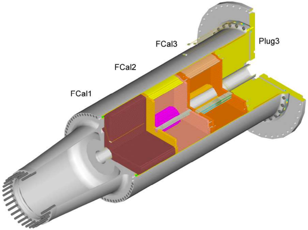
Trigger selects "interesting" events. Collisions occur at a rate of 40 MHz, events recorded at $\sim$400 Hz (bandwidth).

- Level 1 (L1) (hardware)
  - Calorimeter Trigger (L1Calo)
    - Jet triggers (will be discussed later)
  - Muon Trigger (L1Muon)
  - Decision required within 2.5 μs
- High Level Trigger (HLT) (software)
  - Level 2 (L2)
    - Decision required in 40 ms
  - Event Filter (EF)
    - Decision required in 4 s
    - Not used in 2010

The Atlas Forward Calorimeters

- Consist of one EM module (FCal1) and 2 hadronic modules (FCal2 and FCal3).
- Covers pseudorapidity range $3.1 < |\eta| < 4.9$, approx 5m from IP.
- High particle flux at large $|\eta|$ requires novel design.
  - Liquid Argon (LAr) gaps are much smaller than for conventional calorimeters.
- Located in a region not covered by tracking, in-situ studies are difficult.



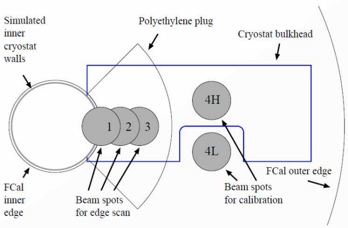


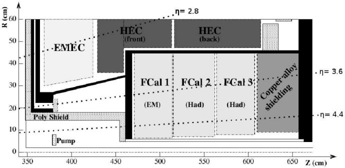
Hadronic Calibration

- First step in calibrating calorimeter is obtaining the “EM scale” calibration
  - Calibrated response to photons, electrons.
  - Obtained from test beam studies.
- Hadronic showers are more complex
  - Part of the energy in a hadronic shower is “invisible”.
  - EM component of the shower scales nonlinearly with the energy of initial hadron.
  - Calorimeter response non-linear with respect to energy of initial hadron.
- Additional calibration required to reconstruct energy of hadronic particles.
  - Simple method used for FCal beam test.
  - More complex methods used at ATLAS, derived from simulation.
    - Requires a good simulation of the detector response.

Beam Test Motivation

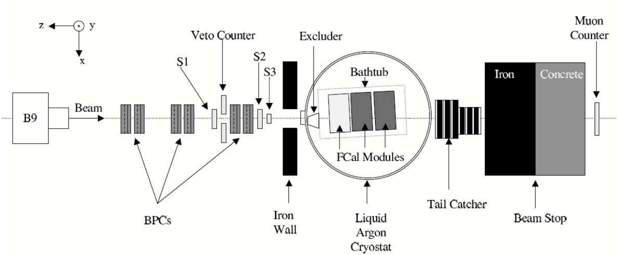
- Obtain EM scale calibration (4L).
- Study effect of additional material on detector performance:
  - Response
  - Resolution
- Validate Monte Carlo simulations of the FCal (4L/4H).
  - Performance
  - Shower shapes
- FCal subjected to beams of electrons and hadrons at energies of 10-200 GeV.





Beamline Setup

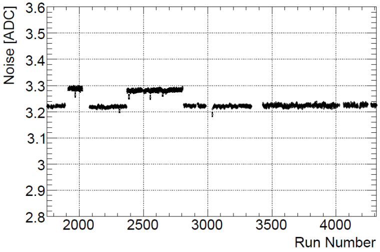
CERN H6 Beamline



- Scintillators (S1,S2,S3) used for triggering.
- BPCs (MWPCs) used to reconstruct track.
- Both used for event selection (single particle).
- Beam test setup modelled in GEANT4 simulation.

Monte Carlo Simulation

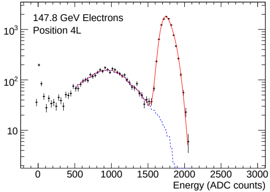
- Simulation of test beam developed using `GEANT4`, within `Athena` framework.
  - Describes all beam elements downstream of B9 magnet.
- Obtained results using QGSP_BERT, QGSP_BERT_HP and FTFP_BERT hadronic physics lists.
- Electronic noise used in simulation is measured from data
  - Noise varied over time - different noise levels at (e.g.) different beam energies.
  - channel-channel correlations included.



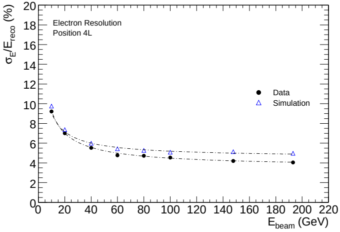
This effect is also accounted for in the data analysis.

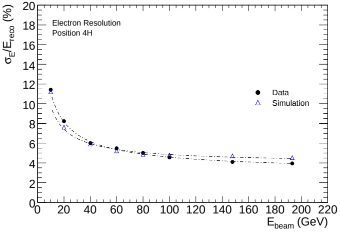
Energy Reconstruction

- Reconstructed track projected to obtain particle impact point on calorimeter face.
- Cylindrical clusters formed by summing energies of cells within radius of 8 cm (electrons) and 16 cm (hadrons).
- Double Gaussian is fit to the peak of the response. For electron beams, hadron contamination is modelled in the fit (using hadron data).



Electron Energy Resolution



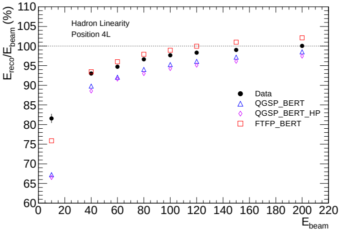


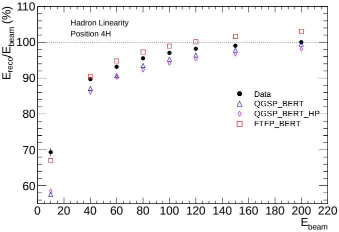
$$\frac{\sigma_E}{\bar{E}} = \frac{A}{\sqrt{E}} \oplus B,$$

A = stochastic term
B = constant term

- Resolution describes the precision with which energy can be reconstructed.
- Noise term ($\propto 1/E$) ommitted - electronic noise subtracted in quadrature from width.
- Resolution in simulation slightly higher (worse) than in data - consistent with other `GEANT4` results.
- Constant term at 4L 15% higher than 4H, in both data and MC.

Pion Response



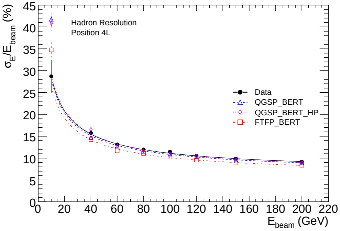


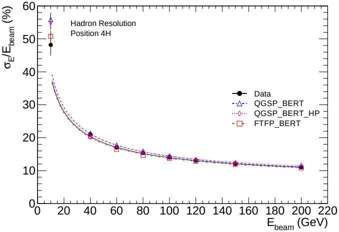
- Pions deposit less visible energy in the calorimeter - require calibration.
- Simple flat weighting scheme used for hadronic calibration - each module has a weight associated with it.

$$E_{\mathrm{cal}} = g_1 E_{1,\mathrm{EM}} + g_2 E_{2,\mathrm{EM}} + g_3 E_{3,\mathrm{EM}}$$

- Weights derived from 200 GeV data used to calibrate data and MC.
- MC results generally within a few percent of data.

Pion Resolution



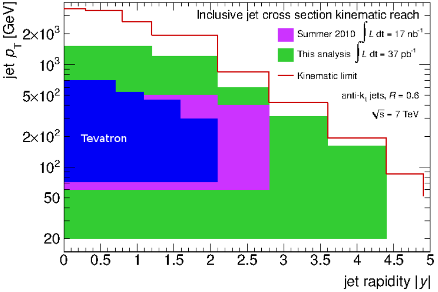


- Resolution at 4L slightly improved compared to previously published result (corrected energy rounding bug).
- Generally good agreement between Data and MC.
- Changes from 4L→4H similar in Data and MC.
  - Effects of additional material are well modelled by the simulation.

Testbeam summary

- Analysed data at 4L and 4H - response and resolution of the FCal have been measured using beams of electrons and hadrons at energies of 10-200 GeV.
- Simulation agrees well with data - Changes from 4L $\rightarrow$ 4H well modelled by simulation.
- Validation of MC for the FCal, important as all ATLAS hadronic calibrations are derived from MC.
- Shower shapes and topological clusters have also been studied.

Inclusive Jet Cross-Section

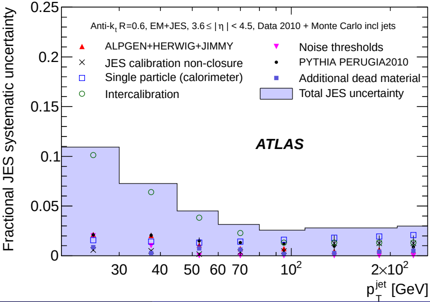


$$y = \frac{1}{2}\log\left(\frac{E + p_z}{E - p_z}\right)$$

- Inclusive Jet Cross-Section - all jets in each event contribute.
- QCD measurement in a region of phase space not previously explored. Allows study of pQCD + models for soft QCD.
- First ATLAS measurement (purple) used $17\mathrm{nb}^{-1}$ of early data.
- This analysis used full 2010 dataset (green) - $37\mathrm{pb}^{-1}$ of data. Covers kinematic region $p_\mathrm{T} > 20\mathrm{GeV}$ and $|y| < 4.4$.

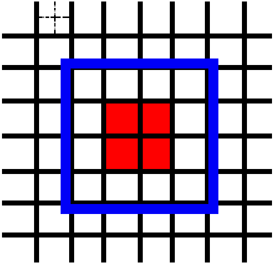
Jet Reconstruction and Calibration

- Jets defined using anti-k_t algorithm on topoclusters, with $R = 0.4$ and $R = 0.6$.
- EM+JES used to calibrate jets - correction factor applied to EM scale jet energy. Binned in $|\eta|$ and p_T.
- Calibration derived from MC - important to understand simulation.
- Uncertainty in calibration is generally around 3-5% at high p_T- Dominant contribution to cross-section uncertainty.



Jet Triggers

- Forward jet triggers (FJ) identify jets in the FCal, central jet triggers (J) identify jets elsewhere.
- Trigger towers are formed from analog sums of calorimeter channels
- "Jet Elements" are formed by grouping trigger towers (0.2×0.2 in $\eta - \phi$)
- Sliding window algorithm used to find jets at L1, identify a Region of Interest (ROI)
- At L2, cone based algorithm run on cells within the ROI



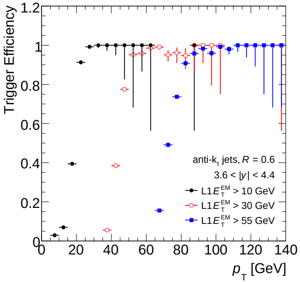
Trigger Efficiency

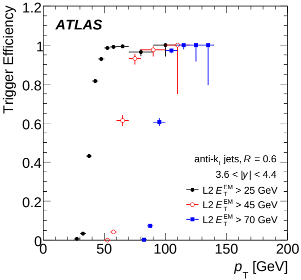
- The inclusive efficiency of a trigger is defined as

$$\epsilon_{\mathrm{inc}} = \frac{N_{\mathrm{triggered,inc}}}{N_{\mathrm{reference}}},$$

- $N_{\mathrm{reference}}$ is the number of jets in a reference sample.
- $N_{\mathrm{triggered,inc}}$ is the number of jets from events in reference sample that meet the trigger condition.
- Binning $N_{\mathrm{triggered,inc}}$ and $N_{\mathrm{reference}}$ in p_{T} allows the efficiency to be described as a function of p_{T}.
- Triggers are used to select events above their "plateau point". Sum bins of $N_{\mathrm{triggered,inc}}$ and $N_{\mathrm{reference}}$ and take the ratio. The plateau point is where this ratio drops below 99%, such that trigger is at least 99% efficient above this point.

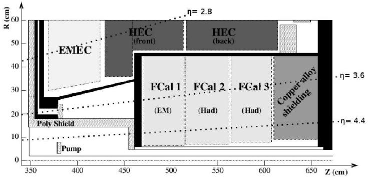
Trigger Efficiency - Forward Bin ($3.6 < |y| < 4.4$)

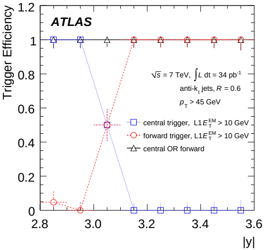




- Trigger efficiencies at L1 (left) and L2 (right), for jets with $R = 0.6$ in the FCal ($3.6 < |y| < 4.4$)
- L1 triggers reach plateau at 23 GeV, 60 GeV and 99 GeV, and are used to collect data above 30 GeV, 80 GeV and 110 GeV, respectively.

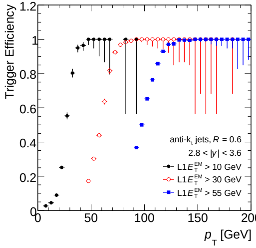
Transition Bin Triggers

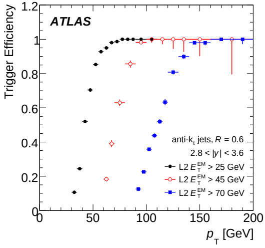




- Transition bin covers the region $2.8 < |y| < 3.6$.
- Neither the Central jet trigger or the Forward Jet trigger are fully efficient in this range.
- Need to use a combination of the two ("OR") to select jets in this region.

Trigger Efficiency - Transition Bin $(2.8 < |y| < 3.6)$





- Trigger efficiencies at L1 (left) and L2 (right), for jets with $R = 0.6$ in the Transition bin $(2.8 < |y| < 3.6)$

Transition Bin Cross-Section

- When a single trigger is used, Jet cross-section is given by

$$\sigma = N_{jets} \left(\sum_i \frac{\mathcal{L}_i}{S_i} \right)^{-1},$$

where the sum runs over LumiBlocks, $\mathcal{L}_i$ is the integrated luminosity and S_i is the trigger prescale.

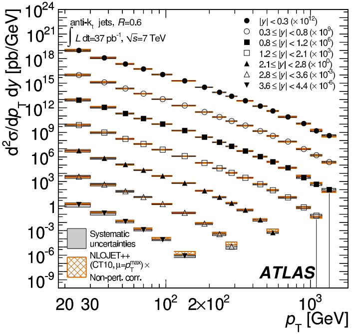
- When using the OR of the triggers, events are divided into three classes: those which meet the forward trigger condition (10), the central trigger condition (01), and both trigger conditions (11). The jet cross-section is then

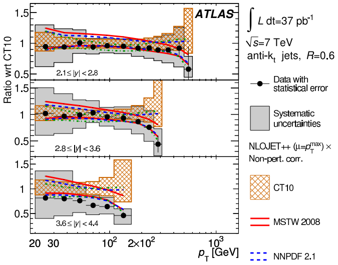
$$\sigma = \frac{N_{01}}{\mathcal{L}_{01}} + \frac{N_{10}}{\mathcal{L}_{10}} + \frac{N_{11}}{\mathcal{L}_{11}} \tag{1}$$

where N_{xx} is the number of jets counted from events of that type, and

$$\mathcal{L}_{11} = \sum_i \frac{\mathcal{L}_i \left(S_{i,01} + S_{i,10} - 1 \right)}{S_{i,01}\, S_{i,10}}.$$

Inclusive Jet Cross-Section Results





- Theoretical predictions obtained using NLOJet++ with CT10 Parton Distribution Functions, generally good agreement.
- Of the results obtained from NLOJet++, the MSTW2008 pdf gives the best agreement with data.
- Best agreement between data and theory obtained from Powheg, when interfaced to Pythia (AUET2B tune).

Summary

- Data from 2003 beam test of ATLAS forward calorimeter has been analysed, and compared to results obtained from Monte Carlo. The simulation agrees well with the data, and effects associated with additional upstream material are well modelled, providing validation of the simulation.
- Inclusive Jet and Dijet (backup) cross-sections have been measured using 37 pb^{-1} of data collected in 2010. These measurements cover a large kinematic region, coherently probing rapidity region that has not previously been studied at a hadron-hadron collider. Cross-section measurements at CMS use two seperate analyses (different jet definitions) to study jets in the central and forward regions, and there is a gap in the rapidity coverage spanned by these analyses.

Backup slides

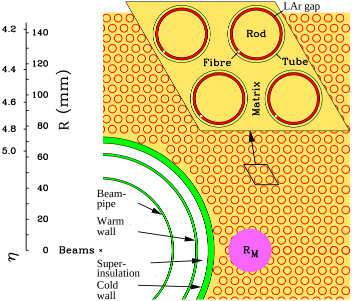
Backup Slides

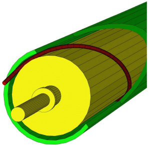
Proton-Proton Collisions

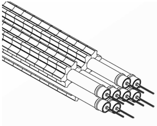
In addition to hard scattering between partons, other processes involved.

- Partons collinearly radiate before (after) hard scatter - initial (final) state radiation.
- Soft scatterings can occur between partons not involved in the hard scatter (Multiple parton interactions - Underlying Event)
- Pile-up
  - At design specifications, ATLAS expects ~ 23 proton-proton collisions per bunch crossing (only $\sim 3-4$ during 2010).
  - An event containing a hard scattering will also contain several soft scatterings between other protons.
  - This additional pile-up energy is corrected for in the EM+JES calibration.

FCal structure







- Electrodes run down length of modules.
- Thin gaps between rod and tube occupied by LAr, sensitive regions.
- Absorbing material is copper in FCal1, tungsten based in FCal2 & FCal3

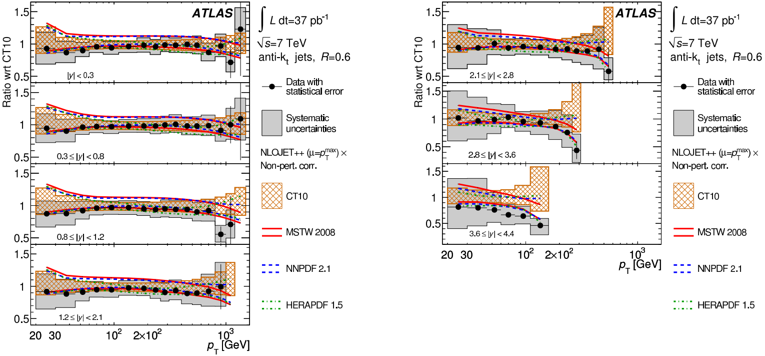
Topological clustering

- Cells clustered based on energy/noise significance.
- "420" scheme used for hadronic clusters
  - If a cell has $|E|/\sigma > 4.0$, it is considered a seed.
  - Adjacent cells are added to the cluster if $|E|/\sigma > 2.0$ (neighbours).
  - Neighbour step is repeated until there are no cells adjacent to the cluster with $|E|/\sigma > 2.0$
  - all "perimeter" cells are added to the cluster (require $|E|/\sigma > 0.0$).
- Topoclusters are used at `ATLAS`
- Don't require tracking information for formation.

Unfolding

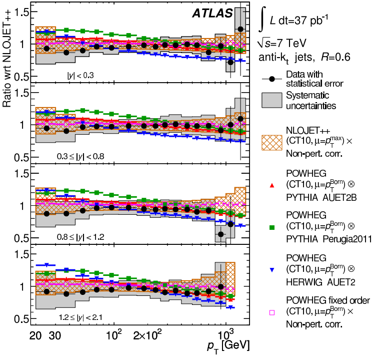
- Jet energies are measured with finite resolution. Jet spectrum falls sharply with p_{T}, so more low p_{T} jets are measured to have high p_{T} than high p_{T} jets are measured to have low p_{T}. Measured spectrum is skewed towards high p_{T}.
- Unfolding is used to correct this effect, based on Monte Carlo. "Truth" jets are fromed from the particles output by the event generator. The interaction of these jets with the detector is then simulated (`GEANT4`), and "reconstructed" are obtained using the same methods as for data. Detector effects can then be inferred by matching truth jets to reconstructed jets and forming a "Transfer Matrix".
- Transfer matrix can then be inverted and applied to measured jet spectrum to obtain a corrected spectrum. This is not a trivial task, the Iterative, Dynamically Stabilised (IDS) method is used.

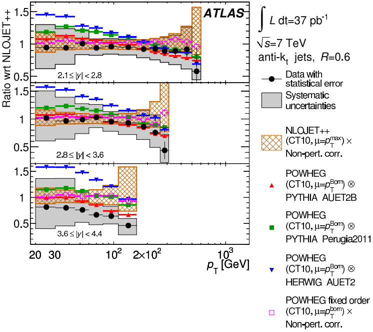
Inclusive Jet results - NLOJet++



Ratio of data to NLOJet++ using CT10 pdf. Ratios of NLOJet++ with other pdfs to CT10 are also shown.

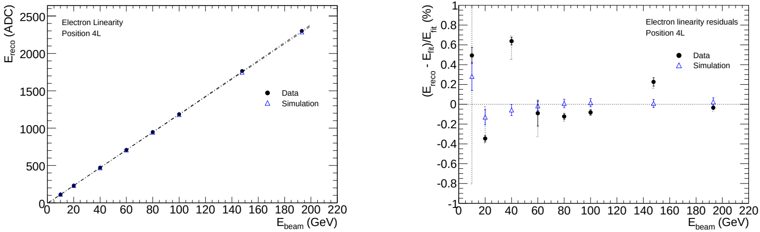
Inclusive Jet results - Powheg





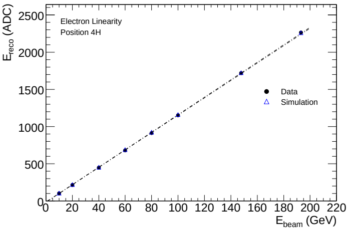
Theoretical predictions obtained using `POWHEG`, interfaced to parton shower MC generators.

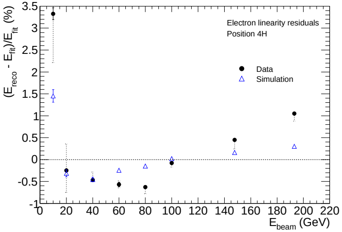
Electron Response Linearity



- Response vs beam energy - expect a linear relationship.
- Slope at 4L gives the EM calibration currently used at ATLAS.
- Good agreement between Data and MC.
- Changes from 4L$\rightarrow$4H (not shown) similar in Data and MC.

Electron Response Linearity (4H)





- Good agreement between Data and MC.
- Changes from 4L→4H similar in Data and MC.

Electron results

linearity result	slope (ADC/GeV)	Intercept (ADC)
Data (4L)	11.966 $\pm$ 0.002	-9.26 $\pm$ 0.07
Simulation (4L)	11.865 $\pm$ 0.003	-6.45 $\pm$ 0.13
Data (4H)	11.693 $\pm$ 0.002	-17.53 $\pm$ 0.10
Simulation (4H)	11.747 $\pm$ 0.003	-15.44 $\pm$ 0.13

	Stochastic Term (% $\mathrm{GeV}^{1/2}$)	Constant Term (%)
Data (4L)	27.0 $\pm$ 0.2	3.58 $\pm$ 0.02
Simulation (4L)	24.7 $\pm$ 0.3	4.56 $\pm$ 0.03
Data (4H)	33.7 $\pm$ 0.2	3.11 $\pm$ 0.03
Simulation (4H)	28.1 $\pm$ 0.3	3.96 $\pm$ 0.03

Linearity and resolution results for electrons

Hadron Resolution results

Results from hadron resolution fits, for data and MC at 4L and 4H.

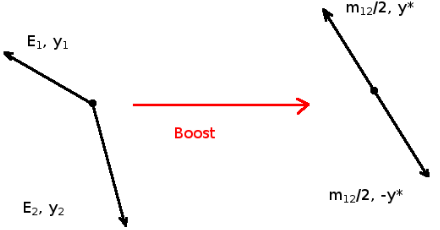
	Stochastic Term (% $\mathrm{GeV}^{1/2}$)	Constant Term (%)
Data (4L)	88.0 ± 0.6	6.79 ± 0.06
QGSP_BERT (4L)	86.2 ± 1.1	6.54 ± 0.18
QGSP_BERT_HP (4L)	90.5 ± 1.1	6.22 ± 0.13
FTFP_BERT (4L)	81.2 ± 1.1	6.04 ± 0.11
Data (4H)	120.7 ± 0.6	6.98 ± 0.07
QGSP_BERT (4H)	127.6 ± 1.1	6.62 ± 0.17
QGSP_BERT_HP (4H)	123.3 ± 1.2	7.58 ± 0.16
FTFP_BERT (4H)	119.2 ± 1.1	6.77 ± 0.15

Dijet Kinematics

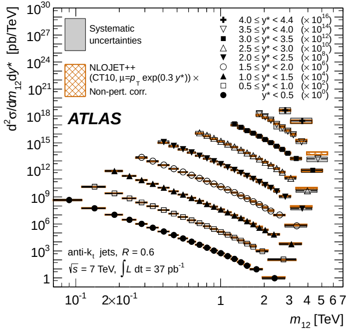
- Inclusive cross-section binned in p_{T}, y.
- Dijet cross-section binned in m_{12}, y^*.
  - describe the dijet kinematics in the COM frame.

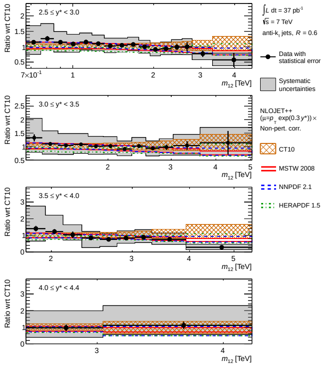
$$y^* = \frac{|y_1 - y_2|}{2}$$

$$m_{12}^2 = (p_1 + p_2)^2$$



Dijet Cross-Section Results





- Trigger scheme used for dijet analysis is similar to that used in the transition bin of the inclusive analysis - Dijet event is considered if either leading jet or subleading jet meets relevant trigger condition.
- Theoretical predictions obtained using NLOJet++ with CT10 Parton Distribution Functions, generally good agreement.
- Best agreement between data and theory obtained from Powheg